Haze removal based on advanced haze optimized transformation (AHOT) for multispectral imagery

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Abstract

Ever-present spatial varying haze contamination in satellite scenes limits applications using visible and near infrared bands of low temporal resolution multispectral satellite imageries. A relative atmospheric correction technique: virtual cloud point (VCP) based on advanced haze optimized transformation (AHOT) is developed for haze removal. It is an improved algorithm of the previous dark object subtraction (DOS) based on haze optimized transformation (HOT). In AHOT, extra steps are added to HOT to remove confusion caused by some land cover types. VCP uses not only lower bound but also upper bound of histogram, so it enlarges digital number (DN) variance reduced by haze, which is not considered in DOS. To evaluate this algorithm, hazy subsets of one Landsat TM and one QuickBird images are employed. Through before-and-after comparison using both true color images and NDVI, it proves that VCP based on AHOT is apparently better than DOS based on HOT, when haze is distributed over urban areas where vegetation is sparse.

Keywords: Haze removal, Advanced haze optimized transformation (AHOT), virtual cloud point (VCP)
1 Introduction

Cloud and haze are two atmospheric effects which limit many remote sensing applications, especially land cover mapping using visible and near infrared bands of low temporal resolution multispectral satellite imageries such as Landsat TM/ETM, QuickBird and so on. Cloud blocks almost all radiation, so substitution is the only way to reduce information loss (Lu 2007). Haze, also called as “thin cloud”, partially obscures the ground. To remove haze obscurity, some atmospheric correction (AC) techniques have been developed and utilized, which can be grouped into three categories: absolute AC using independent data, scene-based absolute AC and scene-based relative AC (Hadjimitsis et al. 2004). Absolute AC using independent data is effective to solve haze contamination, but it needs ancillary data regarding the atmospheric conditions at the time and place of the analyzed scene, which is often impossible to obtain. There remains a need for robust, scene-based AC (absolute or relative) techniques for haze removal.

Some certain scene-based techniques have been developed and utilized for decades (Chavez 1996), such as the well-known dark-object subtraction (DOS) (Chavez 1988; Teillet and Fedosejevs 1995) and dense dark vegetation (DDV) (Kaufman and Sendra 1988; Kaufman et al. 1997). However, scene-wide techniques are only suitable for homogeneous haze conditions. Ever-present spatial varying haze contamination in satellite scenes makes AC more difficult and need advanced scene-based AC techniques that can automatically determine inner-scene haze thickness.

The most popular method to determine haze thickness (usually aerosol optical depth) is DDV which is a scene-based absolute AC based on the stable relationship between a haze-influenced band and a haze-transparent band of dense dark vegetation. Though it has been extended to retrieve heterogeneous haze distribution by interpolation (Liang et al. 1997), this method does not work well if the dense vegetation is not widely distributed over the hazy regions or if the scene is acquired in the defoliate season. To determine haze thickness over a variety of surface conditions, Liang et al. (2001, 2002) proposed a cluster matching technique for TM based on an assumption that each land cover cluster (unsupervised classified using infrared bands) has same visible reflectance in both clear and hazy regions (Liang et al. 2001; Liang et al. 2002). Though these absolute AC techniques are operational in quantitative applications, they all have a precondition that at least a haze-transparent band (such as mid-infrared bands) should be available which makes it unpractical for very high resolution optical satellite imagery which has only visible and near-infrared bands. Moreover, radiative transfer model is too complex for qualitative applications such as land cover mapping.

Radiometric transformation is another way to determine haze thickness. It was noted that haze seemed to be a major contributor to the fourth component of Tasseled Cap (TC) transformation (Crist and Cicone 1984; Richter 1996). Zhang et al. (2002) proposed the haze optimized transformation (HOT) for haze thickness determination, which is an improved two-band version (TM bands 1 and 3) of TC transformation. HOT combined with DOS is proved to be an operational relative AC for TM and high-resolution satellite data (Dal Moro and Halounova 2007; Zhang et al. 2002). However it will cause overcorrection or undercorrection of some surface classes. Moreover, simple DOS is not appropriate to correct multiplicative effect of haze.
In this paper, we present an improved relative AC technique method based on advanced HOT (AHOT) to retrieve digital number (DN) contaminated by ever-present spatial varying haze, rather than absolute AC technique to retrieve reflectance. This method will be detailed in two sections: haze thickness determination using AHOT and haze removal based on AHOT. We select one Landsat TM image and one QuickBird multispectral image acquired in summer as case studies, which are widely used in land cover mapping applications. Both of them are contaminated by spatial varying haze, and the hazy subset will be shown for visual assessment. TM contains urban, suburban and mountainous areas, while QuickBird contains inner urban areas for more complex urban land cover types, which can be used for a universal test. A simple assessment of the effectiveness of AHOT is conducted by visually checking true colour images and comparing NDVI.

2 Haze thickness determination using AHOT

AHOT originates from HOT proposed by Zhang et al. (2002). Feasibility of HOT is based on the fact that blue and red bands of different land cover types, under clear atmospheric conditions, are highly correlated. Therefore, this deviation can be ascribed to haze. HOT has an advantage of unrestrained using condition without requiring haze transparent bands or existence of a given stable land cover. However, Zhang also admitted that correlation is not absolutely tight and some land cover types will cause confusion, such as snow/ice (confused with cloud), bare soil (relatively low HOT) and some water (relatively high HOT) (Zhang et al. 2002). So, red/blue feature space looks like a plane, with confusing land cover on two wings (Fig. 1). Haze causes deviation along one wing. HOT has the negative effect of eliminating residual thematic discrimination differences between these visible bands. Removing the land cover confusion will help reduce the negative effect, and therefore improve HOT based AC technique (Dal Moro and Halounova 2007).

The difference between AHOT and HOT is that we introduce some extra steps making use of spatial information to remove the land cover confusion (Fig. 2). Snow/ice is not considered in AHOT, since it’s better to treat it as cloud and mask it. Details of AHOT are given in the rest part of this section.

2.1 Calculate HOT

HOT calculation can be generalized into two steps. First, select a clear region and extract the fitting straight line of two visible bands (red vs blue) as the clear-sky line. Second, calculate the distance of each pixel from this clear-sky line (Eq. 1) as HOT (Eq. 2) (Zhang et al. 2002). The small alteration is that we do zero adjustment to make average HOT of the clear region be zero, which is important for our haze removal method.

\[
\text{Clear-sky line} \rightarrow b_1 \sin \Phi - b_3 \cos \Phi - a = 0 \quad (1)
\]

\[
\text{HOT} = b_1 \sin \Phi - b_3 \cos \Phi - a \quad (2)
\]

Where \( \Phi \) is slope angle of CL, \( a \) is the intercept of CL, \( b_1 \) and \( b_3 \) are bands 1 and 3.
3 digital numbers (DN), respectively.

For a terrestrial landscape, vegetation is always the dominant land cover, except some special landscapes. In addition, asphalt is the dominant man-made material, paved on roads and roofs. So clear-sky line is mainly determined by these two background land cover types, and their HOTs are close to zero.

From an inspection of other land cover types in TM and QuickBird (Fig. 3a-c), we find that bare soil and water triggers spurious HOT, which agrees with Zhang’s study (Zhang et al. 2002). Building shadow (only in QuickBird) has similar spectral response with water (no direct reflectance), hence, building shadow has slightly high HOT. Other man-made objects are complex in urban areas. Concrete, bright white in a true color image, has slightly low HOT. Colorful objects from blue to red have HOT from very high to very low.

Compared with the two background land cover type (gray in HOT image), the confusing land cover types are either darker or brighter (Fig. 3d-f). In Fig. 3d, we can clearly identify the brighter haze, the lake on the right border, the darker soil in village and bare soil road. In Fig. 3e, a slightly brighter river is on the lower right, while no haze exists in this subset. Instead, the brighter pixels are almost all blue roofs. The darker pixels are almost soil, red roofs and white roofs. The more detailed confusing land cover in urban areas can be distinguished in QuickBird (Fig. 3f).

2.2 Adjust bias of each land cover type (for TM)

If we had a land cover classification map, we could adjust HOT by subtracting average HOT of each land cover type. Then only intra-land-cover variance is left, which is considered as irremovable residue in our study. But land cover classification can not be achieved from heavily contaminated visible bands. Liang proposed the cluster matching technique to replace hazy region reflectance by clear region reflectance in each land cover class, which is resulted from three infrared bands of TM (TM4,5,7) by any unsupervised classification method (Liang et al. 2001; Liang et al. 2002). Using his idea for reference, we subtract the average HOT of clear region in each land cover type to solve the land cover dependent problem of HOT. Unfortunately, this step is not suitable for QuickBird (neither other four-band imageries).

But this step seems to be not efficient as expected. The assumption that land cover types classified using these three infrared bands are nearly the same with that classified using three visible bands can not be applied to some land cover types (Fig. 4). Fifty classes resulted from K-means show that most of them have a stable standard deviation (SD), except class 41, 45, 48, 49, and 50. From the inspection of these fifty classes, we find that class 1, 2, and 3 are mainly water, class 41, 45, 48, 49, and 50 are mixture of other confusing land cover types (soil, concrete and colorful man-made objects). The rest are various subclasses of vegetation (crops, grass, forest and so on) and asphalt.

Fig. 4. Average HOT of fifty land cover classes in the clear region of TM classified by K-means. The last point represents a manually delineated thick haze region as reference.
So this step can correct spurious HOT caused by water and inner variance of vegetation. In Fig. 5, it is impossible to visually distinguish water from background. Also, background becomes more homogenous, improving signal-to-noise ratio of HOT based technique. The rest poor adjusted confusing land cover types need another way. We have tried mask-interpolation method (setting user-defined lower and upper thresholds), but confusing land cover under different haze thickness need changeable thresholds, making this simple method imperfect. A robust method is needed urgently to solve the lower HOT and higher HOT problem. In our approach, they are solved separately in the rest steps.

Fig. 5. HOT after adjusting each land cover of TM. Left is the hazy subset, and right is the clear subset

2.3 Fill sink

To solve the lower HOT problem, we took the HOT image as a digital elevation model (DEM), so local maximum can be regard as peak while local minimum as sink. Lower HOT land cover types form sinks in the DEM, while both higher HOT land cover types and haze form peaks. Filling sinks can solve lower HOT problem, but cutting peaks is useless to solve the higher HOT problem (next step is to separate higher HOT land cover types from haze). In this step, we use a ‘fill sink’ routine, which origins from hydrology.

In hydrology, sink (also: depression, catchment basin) is a very important component of surface topology (Jenson and Domingue 1988). DEM has been widely used to extract drainage network, catchment area/storage (Martz and Garbrecht 1992), while in large-scale geomorphology, small sink is usually considered as erroneous data. So far, some robust algorithms have been proposed to detect and fill sink, among which Planchnon’s is simple and fast (Planchnon and Darboux 2002).

Actually, Planchnon’s ‘fill sink’ operation is a special interpolation method. For each sink, it detects and masks the sink and then replaces it by the minimum of its border pixels. We find it a coincidence that his routine is almost the same as the morphological reconstruction operation in mathematical morphology using a user-defined marker, which is available in the software MATLAB (function ‘imfill’). Details of morphological reconstruction can be found in mathematical morphology books and articles (Soille and Pesaresi 2002). So we simplify the ‘fill sink’ routine into four steps (Fig. 6), and recommend Planchnon’s original paper for more details.

Fig. 6. The ‘fill sink’ routine and it’s pseudo code. A is any large value larger than the maximum of HOT, B is any small value smaller than the minimum of HOT.

After ‘fill sink’ operation, the darker patches disappear and the background becomes darker (Fig. 7a,b). For image display is linear 2% stretched, after the darker patches becoming brighter, dynamic range of pixel values becomes smaller. Efficiency of ‘fill sink’ on QuickBird seems not as good as that on TM (Fig. 7c). The reason is that detailed urban land cover is more complex. In addition, previous step is not performed on QuickBird to alleviate its mosaic appearance.

There are two deficiencies in this step. First, if a darker patch is adjacent to the image border, it will not be filled. Ignore it or modify the second step in ‘fill sink’ routine by ‘Marker’s border pixels=HOT’s border pixels (where HOT’s border pixels smaller than a user-defined threshold), while all the other pixels=B’. Second, A better
alternate ‘fill sink’ operation is to interpolate sink via operators that concern multi-border pixels, such as spline or linear operators, but it will ruin the next step (flatten peak).

Fig. 7. HOT after fill sink operation on Fig. 3d-f.

2.4 Flatten peak

As mentioned in the previous step, the higher HOT land cover types and haze are both peaks. So we should flatten the former (hereafter, we use term ‘pseudo haze’) and keep the latter, and the key is to find the difference between them. As we see in Fig. 7b, c, pseudo haze can be visually identified according to its sharp borders where sudden change between land cover types occurs, no matter the pseudo haze is water or man-made objects. If the pseudo haze is adjacent to soil and interpolation method in the previous step is not as advised, sharp borders may not be inevitable. To automatically mask pseudo haze, we developed a ‘flatten peak’ routine based on the sudden change phenomenon on the borders. We summarized this routine into four steps (Fig. 8).

Fig. 8. The ‘flatten peak’ routine and its pseudo code. B and n are both user defined parameters.

1) Morphological erode ‘n’ times using 3×3 window as structuring element so that each pixel value (HOT) will be finally replaced by the minimum of neighbouring pixels in (2n+1)×(2n+1) window. Only once morphological erosion using (2n+1)×(2n+1) window as structuring element is not a feasible substitute, since we need information from the gradual morphological erosion needed in the second step. User defined ‘n’ should be large enough to remove all pseudo haze (haze doesn’t matter), which can not be recovered by morphological reconstruction in the third step.

2) Record changes after every morphological erosion and find the maximum which represents the sudden change on the borders. Pseudo haze are pixels with maximal change, but not vice versa.

3) Morphologically reconstruct the marker image resulted from previous morphological erosion, using the HOT image before morphological erosion as mask. After this step, only local maximum HOT belonging to pseudo haze will not be recovered, while the rest will be recovered.

4) Mask the pixels whose maximal change is larger than the user defined threshold B and HOT not recovered in the third step, and then interpolate using any proper operators.

Visually, this step can efficiently remove pseudo haze (Fig. 9). The background variance which we considered as residue in our study is left to future work. Though the background seems mosaic in Fig. 9c, variance is acceptable, which will be assessed in the next step.

Fig. 9. HOT after flatten peak operation on Fig. 7a-c.

2.5 Adjust bias

After the former two steps, average HOT of the predefined clear region is not
zero anymore. To adjust the bias, average HOT of the clear region is subtracted from the whole HOT image.

Compared with Fig. 4 (representing original HOT), our haze thickness determination method is apparently more accurate. Variance in the clear region is evidently reduced and the haze region is seldom disturbed, which will benefit the haze removal procedure in the next section.

Fig. 10. Efficiency of the former fill sink and flatten peak steps. A, average HOT of the fifty land cover classes in the clear region of TM after the two steps. The last point represents a manually delineated thick haze region as reference. B, standard deviation change of the clear region of QuickBird.

Finally, HOT after process via the previous extra steps is improved greatly, so we name it as AHOT.

3 Haze removal based on AHOT

To remove spatial varying haze based on HOT, Zhang sliced the HOT image and applied DOS method to each slice (Zhang et al. 2002). Visually, a hazy image can be deblurred efficiently, but multiplicative effect of aerosol scattering is not considered. Aerosol scattering not only increases apparent surface reflectance over dark objects but also reduces the apparent surface reflectance over bright object (Fraser and Kaufman 1985). So we introduce a virtual cloud point (VCP) method based on AHOT, considering both lower-bound and upper-bound value of each AHOT slice (Fig. 11). The approach for each band is detailed into five steps as follows:

1) Choose a hazy region that has spatially homogenous land cover composition and spatial varying haze over it. If that region does not exist, use the whole image instead.

2) Slice the hazy region with a proper AHOT interval (in our case, 1 for TM and 2 for QuickBird), to segment the whole hazy region into several discrete regions with different haze thickness. The AHOT interval should be moderate lest slice number or pixel number of a slice would be too small. Then, get rid of negative AHOT slices and those slices whose pixel number is too small (always the rear ones).

3) Find the lower-bound and upper-bound value of DN histogram in each slice. Considering the unstableness of minimum and maximum value (Dal Moro and Halounova 2007), choose the xth and (100-x)th percentile as lower-bound and upper-bound value respectively (in our case, x=2)

4) Regress the two bounds respectively using linear function and take the intersection point ([AHOTvcp, DNvcp]) for each band as the thickest haze, which can be considered as VCP.

5) Centrally project all pixels ([AHOT, DN]) onto the vertical line (AHOT=0) to get the final image using Eq. 3.

\[ DN_{result} = \frac{(DN \times AHOT_{vcp} - AHOT \times DN_{vcp})}{(AHOT_{vcp} - AHOT)} \] (3)

Fig. 11. Virtual cloud point (VCP) method. Taking the TM blue band for example. a is the VCP, which is the point of intersection of the two regression lines of upper bound and lower bound. b is an example hazy pixel, and c is b after haze removal.

VCP stableness is tested by using different lower percentiles (upper percentiles=100-lower percentiles) from 1 to 49 (Fig. 12). It is proved feasible to use any lower percentile from 1 to 20, whose range is wide enough.
4 Result

A simple assessment of the AHOT method is conducted by comparing the images before and after haze removal. Fig. 13 shows the true color images of the subsets illustrated in the method section. For comparison, results corrected using VCP based on AHOT and DOS based on HOT (i.e. Zhang’s method) are both present. In TM, both of them perform well in the suburban and mountainous area (Fig. 13a). That is because the dominant land cover is vegetation, which does not trigger spurious HOT. Furthermore, vegetation presents low blue and red bands reflectance, close to the lower bound of histogram in each slice, which are both corrected by VCP and DOS.

For the urban area in TM and QuickBird images, VCP is superior to DOS (Fig. 13b,c). VCP reserves colorful objects in the urban area, and removes haze cleaner than DOS. DOS is not able to separate blue man-made objects from thick haze (large HOT slices), so DOS performs poor to correct thick haze. In the DOS corrected images, blue objects turn to gray, while red objects are reserved, since only positive HOT pixels are processed. Soil next to the lower right corner of QuickBird image is brighter than it should be.

Fig. 13. Results of the previously mentioned subsets of TM and QuickBird after haze removal. The upper is VCP based on AHOT and the lower is DOS based on HOT.

Fig. 14 shows how DN (e.g. blue band) and NDVI are strongly influenced by severe haze conditions. Multiplicative effect in the hazy subset of TM image seems to be not well corrected by VCP. The variance decreases with AHOT and the scatter plot seems only rotated, just like the result of DOS. As explained in the visual assessment on true color images, the reason is the dominance of vegetation under thick haze. Multiplicative effect in QuickBird is corrected well, since variance under thick haze is enlarged. The performance of VCP on NDVI of both TM and QuickBird images are proved to be good. More true color subsets are present to show the results of VCP based on AHOT (Fig. 15).

Fig. 14. DN (e.g. blue band) vs AHOT and NDVI vs AHOT before haze removal (left), after DOS (middle) and after VCP (right). The upper four are the hazy subset of TM, and lower four are QuickBird. The middle ones are processed by DOS using HOT.

Fig. 15. Other example subsets corrected using VCP.

5 Conclusion

We proposed a relative atmospheric correction technique to remove spatial varying haze contamination. Our work is an improvement of the previous work (Dal Moro and Halounova 2007; Zhang et al. 2002). Compared with the original haze removal method DOS based on HOT, we improved both the haze thickness determination and haze removal method.

Haze thickness determination is an advanced HOT (AHOT) with some extra steps added to HOT to remove the confusion caused by some land cover types. These extra steps can correct spurious HOT caused by water and inner variance of vegetation,
remove local darker patches caused by lower HOT land cover types such as soil, man-made red objects (almost roofs), white objects (concrete), and remove pseudo haze which are almost man-made blue objects (almost roofs). These extra steps are optional depending on quality of HOT. The more diverse land cover types are, the more steps you need. After haze thickness determination, variance of AHOT in the clear region exists in a tolerable amount, which is considered as residue left to future work.

Haze removal method is a virtual cloud point (VCP) method that will enlarge the DN variance reduced by haze. After VCP ([AHOT\textsubscript{vcp}, DN\textsubscript{vcp}]) is determined, all pixels ([AHOT, DN]) are centrally projected onto the vertical line (AHOT=0) to obtain the dehazed image. Stableness of VCP is tested.

Simple assessment of this technique is performed on hazy subsets of one Landsat TM and one QuickBird images. Through before-and-after comparison using both true color images and NDVI, it proves that VCP based on AHOT is apparently better than DOS based on HOT, when haze is distributed over urban areas where vegetation is sparse.

Further, study is need for better performance of the VCP based AHOT technique. First, AHOT is very time consuming, due to the morphological reconstruction operation in ‘fill sink’ and ‘flatten peak’ routines. Second, intra-land-cover variance needs to be reduced. This technique is developed for land cover mapping applications, and needs further validation using more imageries containing various kinds of land cover types.

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Reference


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